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Component level strategies for exploiting the lifespan of steel in products

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ABSTRACT

Approximately 40% of annual demand for steel worldwide is used to replace products that have failed. With this percentage set to rise, extending the lifespan of steel in products presents a significant opportunity to reduce demand and thus decrease carbon dioxide emissions from steel production.

This article presents a new, simplified framework with which to analyse product failure. When applied to the products that dominate steel use, this framework reveals that they are often replaced because a component/sub-assembly becomes *degraded*, *inferior*, *unsuitable* or *worthless*. In light of this, four products, which are representative of high steel content products in general, are analysed at the component level, determining steel mass and cost profiles over the lifespan of each product. The results show that the majority of the steel components are underexploited – still functioning when the product is discarded; in particular, the potential lifespan of the steel-rich structure is typically much greater than its actual lifespan. Twelve case studies, in which product or component life has been increased, are then presented. The resulting evidence is used to tailor life-extension strategies to each reason for product failure and to identify the economic motivations for implementing these strategies. The results suggest that a product template in which the long-lived structure accounts for a relatively high share of costs while short-lived components can be easily replaced (offering profit to the producer and enhanced utility to owners) encourages product life extension.

1. Introduction

Over two million fridges and freezers are thrown away in the UK each year. The average lifespan of these refrigerators is eleven years, with newer models often only lasting half that time (BBC, 2004). Such swift replacement is often attributed to compressor failure. Over a period of ten years, lubricant loss from the compressor causes the small bearings to wear out. With compressor replacement cost comparable to that of a new refrigerator, consumers typically choose to replace rather than repair. The other components in a refrigerator, which account for the majority of the metal content, are still functioning at product end-of-life: the outer case, door, interior fittings and heat exchanger are all working when the fridge is discarded. These components could be used for longer, and are therefore currently under-exploited. Hence, the title of this article refers to 'exploiting' the long functioning lifespan of steel in products, as opposed to 'extending' the lifespan of components that may already be functioning at product end-of-life.

The refrigerator is just one example of how the potential lifespan of the components in a product are poorly exploited; the discarded goods in nations' scrap yards suggest this is inherent in 'throwaway societies'.

The replacement of discarded products drives production and emissions from industry. This paper investigates how to increase the lifespan of a product's **steel** components, as reducing steel production would have the greatest impact on industrial emissions; the production of steel accounts for more emissions than any other material. In 2008, it accounted for approximately 9% of the world's anthropogenic carbon dioxide emissions attributed to energy and processing (IEA, 2008). Industrial data reported by Worrell et al. (2007) and BCS (2007) shows that most of the energy needed in the manufacture of steel products is used in the creation of the liquid metal, not in post-solidification forming and fabrication. The liquid metal is produced by one of two routes: the reduction of the metal oxide found in naturally occurring iron ore (primary production) or by melting scrap (secondary production). Assigning a single figure emission intensity to steel production is complex, as it depends on the relative scale of primary and secondary production and the carbon intensity of the electricity supply. However, Milford et al. (2011) provide approximate ranges of carbon dioxide intensities

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(from 100% primary to 100% secondary) equal to 1.6–0.4tCO_2/t of steel. Allwood et al. (2010) predict that from 2008 to 2050 global demand for steel will double. Moreover, they predict that the share of steel production required to replace buildings, equipment, transport and other steel products will increase from 40% to 80% in this period. In light of this, reducing demand by exploiting the lifespan of steel in products could help meet the IPCC's target of reducing global emissions to half of 1990 levels by 2050. An analysis equivalent to that set out in this paper could be conducted for sources of embodied emissions other than steel.

New products are often more efficient than older ones; there is, therefore, a trade-off when extending the life of a product between saving the embodied emissions associated with new production and failing to take advantage of the latest efficiency improvements. This trade-off has been well studied, for example with regard to product remanufacture by Gutowski et al. (2011), product design and utilisation decisions by Skelton and Allwood (2013) and product reuse by Devoldere et al. (2009). In addition, the optimal life of a range of products that face this trade-off has been calculated for cars by Kim et al. (2003), for fridges by Kim et al. (2006) and for air-conditioning units by De Kleine et al. (2011). However, these papers assume that use phase emissions improvements can only be achieved through product replacement. The product upgrade strategies put forward by this paper could be used to secure use phase emissions improvements while prolonging the life of the structural core of products. As a result, although the pursuit of use-phase emissions improvements is not tackled directly by this paper, it is compatible with its findings.

The literature on design for long-life components and products is focused on methods to repair and upgrade using three related strategies: standardisation, modularity and functional segregation.

Standardised components and reversible, uniform joints facilitate easy replacement and adjustment because the same tools and techniques can be used. Webster and Costello (2005) suggest establishing a standardised 'kit of parts' for steel framed buildings, determining a limited number of regular component sizes predrilled with boltholes at set intervals.

Modular design separates a product into distinct components/sub-assemblies with standardised interfaces, usually with reversible connections so that they can be easily replaced and upgraded. Palani Rajan et al. (2005) attempt to assess the effect of modularity on products' lifespan using a "change modes and effects analysis" for seventeen consumer goods. They assess the likelihood of a product being discarded after potential changes to how it is used (e.g. a kitchen chair now used as a computer chair) and find that greater modularity increases the lifespan of the product because it is more adaptable (e.g. a multi-bit screwdriver is more adaptable than a fixed-bit equivalent).

The first step in functional segregation is to identify the function that each element of a product performs. Once isolated, the product or component can be redesigned so that only the elements most susceptible to failure need be replaced. Reversible connections aid functional segregation by allowing easy, quick replacement; Morgan and Stevenson (2005) and Bogue (2007) both consider this a critical enabler of longer lifespan products. Durmisevic and Brouwer (2002) argue that traditional construction techniques encourage integration rather than segregation of components, causing demolition of buildings when only small alterations are required.

Brand (1994) introduces a useful tool to analyse functional segregation by examining the interaction between components within a product. He distinguishes six systems within a building that he depicts as layered upon each other. Each layer changes at a different rate and affects the adjacent layers. Brand notes that building alteration decisions are usually based on the slower-changing layers (e.g. structural capacity), but occasionally a faster-changing layer causes major alterations because it cannot be modified independently (e.g. installing heavy equipment requiring structural strengthening). Cooper and Allwood's (2012) analysis on reusing components at product end-of-life shows that many components are still functioning even if the product has become degraded. For example, wear of the engine often leads to car replacement, even though many other car components are not degraded. In this paper, the time for which these non-degraded components would continue to function is termed 'residual lifespan'.

There are no studies that analyse the causes of failure of steel products and that assess the extent to which failure occurs at the product rather than the component level. In light of these findings, this study addresses the following questions:

1. Why are steel intensive products replaced?
2. Do we exploit the steel in products?
3. How can we reduce demand for steel by better exploiting the steel components in products?
4. What pragmatic strategies are associated with these objectives?
5. What would motivate us to adopt these strategies?

2. Why are steel intensive products replaced?

The causes of product failure are multifaceted, ranging from inevitable physical degradation over time, to the deliberate curtailment of product life by producers seeking to force replacement purchases, to the voluntary premature replacement of products by consumers in the pursuit of psychological (as opposed to purely functional) benefits. Efforts to create a single set of reasons for product failure from these various influences include: Woodward (1997), who distinguishes between functional lifespan, physical lifespan, technical lifespan, economic lifespan, social and legal lifespan; Cooper (2005), who makes the distinction between absolute (forced) and relative (unforced) obsolescence; Thomsen and van der Flier (2011), who focus on buildings and identify four types of failure along two axes (endogenous–exogenous/physical–behavioural); and van Nes and Cramer (2006) who define four types of failure (wear-and-tear, improved utility, improved expression and new desires).

In order to examine life extension strategies to reduce steel demand, a set of failure modes is required that applies to all the key end-uses of steel, and is pertinent to both household and commercial product replacement decisions. Table 1 displays the failure framework constructed for this purpose, containing four failure modes. Further information on how this proposed failure framework relates to other existing similar frameworks is provided in the thesis, Skelton (2013).

The two rows of the framework distinguish between failure that arises from a change in the state of the product, and failure that arises from a change in the desires of the user. The columns distinguish between changes that affect only the current individual product and user, and more systemic changes that come about through developments elsewhere in the market. These systemic changes could be due to the performance of rival products, changes to the environment in which the product is used, or alterations in the regulations that govern its use.

The failure modes – *degraded*, *inferior*, *unsuitable* and *worthless* – have been applied to Cooper and Allwood's (2012) catalogue of steel products, which includes all products that account for at least 1% of global end-use demand for steel. This was done by mapping the catalogue's detailed causes of failure onto the failure framework using the definitions presented in Table 2.

Fig. 1 combines the resultant information on product failure with data on the final destination of global steel production and the average life of steel products from Cooper and Allwood (2012).

Table 1
Product failure framework.

The performance of the product has declined. . .	**Degraded** . . .relative to when it was bought	**Inferior** . . .relative to what is currently available
The desire for the product has changed. . .	**Unsuitable** . . .in the eyes of its current user	**Worthless** . . .in the eyes of all users

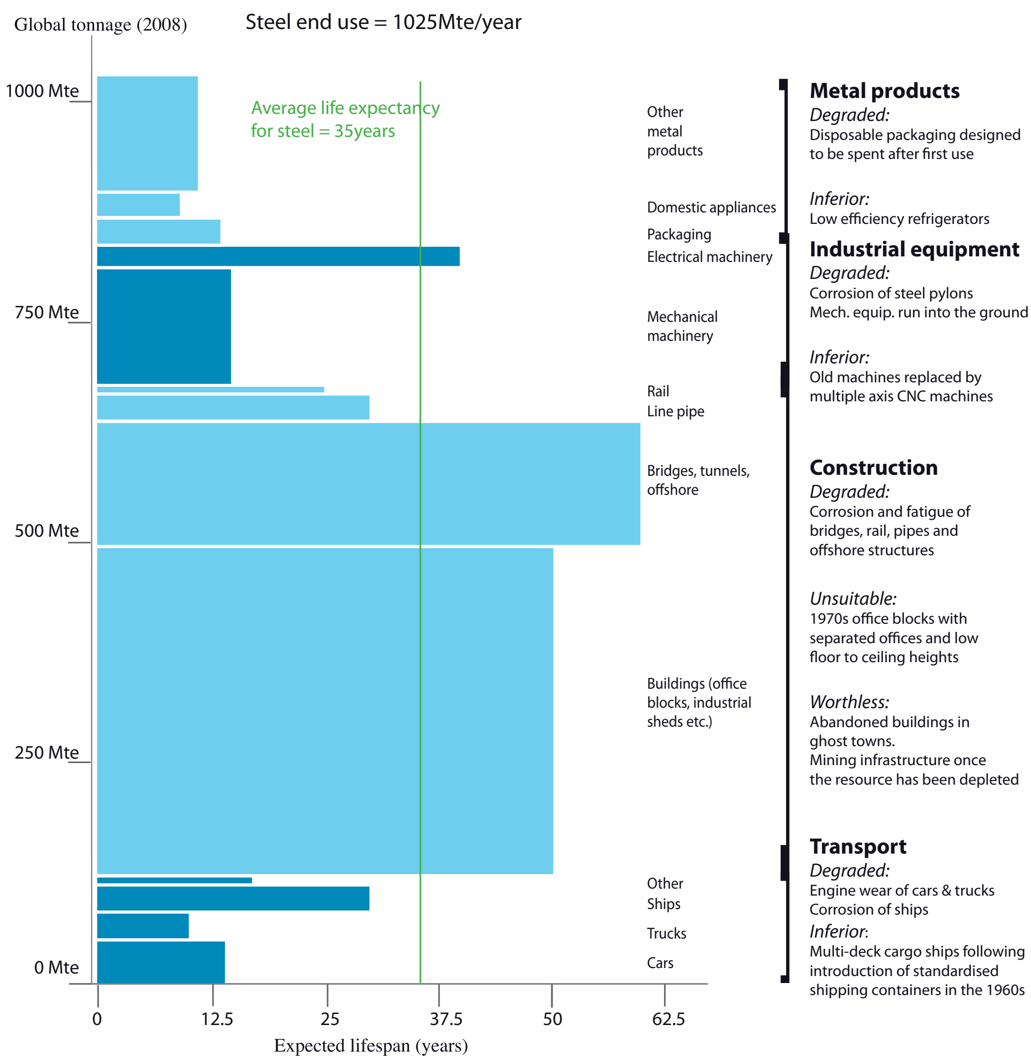


Fig. 1. Expected lifespan and causes of failure of steel products.

Table 2
Mapping detailed reasons for product failure onto the failure framework.

Degraded Wear Fatigue Accidental damage Product spent Product repair not economically viable Scheduled life reached	**Inferior** Rival product offers enhanced functionality Rival product offers lower costs Technology superseded
Unsuitable Change in circumstance Change in preferences Changes in legislation that effect requirements placed on products	**Worthless** Legislation that prohibits use Changes in the environment in which immobile products are used

The share of total, global production accounted for by each product is plotted on the y-axis; the expected lifespan of the products in each category is shown on the x-axis; and examples of the causes of product failure are given on the right hand side of the figure.

Fig. 1 shows that the average expected product lifespan is thirty-five years, ranging from fifty-two years in construction to eleven years in metal products. The relatively short lifespan of metal products is due to short-lived domestic appliances, such as refrigerators, and disposable steel packaging, such as food cans.

Degraded was the most common failure mode of steel products included in the catalogue, affecting more steel-intensive product groups than any other failure mode. Common *degraded* failures include corrosion and fatigue in infrastructure (for example line pipe); packaging designed to be 'spent' after first use (for example aerosol cans); wear of mechanical sub-assemblies in a transport or industrial product (for example engine wear causing a whole car to be scrapped). Due to established reuse routes (e.g. for second hand

Table 3
Component level data sources.

Product	Steel mass	Potential lifespan and failure mode of components
Washing machine	Park et al. (2006)	ISE Appliances (2011) Product Lifespan Institute (2008) U.S. Department of Housing and Urban Development (2000)
7-Storey office block	Goodchild (1993)	Scheuer (2003) Sturgis and Roberts (2010) Treloar et al. (1999) Arup (2011)
Car	Information received from a car manufacturer	Information received from a car manufacturer
5m Steel plate rolling mill	Information received from an industrial equipment manufacturer	Information received from an industrial equipment manufacturer

cars) *Inferior* failures were found to be relatively rare but do occur, for example, when refrigerators with poor efficiency are replaced with newer, more efficient versions. A significant share of product replacements occur because of a change in users' desires. Buildings are the most significant example: their steel elements undergo negligible deterioration and they are demolished because they become *Unsuitable* (for example open plan offices are now preferred over individual units) or *Worthless* due to more systemic changes in preferences (for example derelict buildings in ghost towns).

3. Do we exploit the steel in products?

To assess if steel components are fully exploited a comparison between the actual life of steel products and the potential life of their components is required. In order to make this comparison, four products – which represent the four major end-use steel sectors – are analysed at the component level. This analysis first identifies the products' actual lifespans, reasons for failure and key components. Typical data on the key components' steel content (by mass), and potential lifespan are then collected from industrial partners and from published, product-specific literature. The representative products are a washing machine (metal products), a car (transport), an office block (construction), and a 5m steel plate rolling mill (industrial equipment). Table 3 shows the data sources that were used to compile the component level information.

Data from the industrial equipment manufacturer and car manufacturer were supplied on condition of anonymity.

The mass and lifespan data for the products' components are presented in Table S1 of the Supporting Information (S.I.). These data are used to create 'step-graphs' of each product's cumulative mass over time, accounting for both the initial steel content used in production and the steel within replacement components. These 'step-graphs' are shown in Figs. 2 and 3. Each coloured line represents the cumulative mass of a component over time. Any vertical slice of the graphs sums to their products' cumulative mass. The length of each flat section represents a component's lifespan, and each 'step' indicates component replacement, increasing that component's and product's cumulative mass. The failure of a critical component (always shown in red) causes the product to be discarded. The dashed vertical line shows product end-of-life; any horizontal line to the right of this shows residual lifespan of a functioning component currently discarded with the rest of the product. A product's steel demand rate – its cumulative mass divided by its lifespan – is equal to the gradient of the grey line from the origin to the intersection of the cumulative product mass and product end-of-life lines.

Fig. 2 shows the cumulative mass over the lifespan of a washing machine. Typically, no components in a washing machine are replaced before it is discarded. Subsequently, there are no 'steps' in Fig. 2, and the cumulative product mass is equal to the initial mass of 40 kg. Washing machines are typically discarded after six years, due to wear of inaccessible bearings within the drum casing. The structure, accounting for over half of the steel, has a potential lifespan of eighteen years, but is used for just six years. This twelve year residual life (the difference between the actual life of the structure and its potential life) means that a significant share of the steel in the washing machine is under-exploited.

Trends towards sealed sub-assemblies have deterred individual replacement of washing machine components; however, for other products component replacement is more common and this helps exploit the long-lasting structural steel. Fig. 3 presents the cumulative steel mass over time for a car, office block and rolling mill respectively.

A car's engine is scrapped due to cylinder wear after thirteen years, when the structure has eight years of potential life remaining, and the transmission (gearbox) maybe relatively new. The internal planning of an office block has usually been replaced a number of times until the owner's desired internal plan becomes incompatible with the structure and it is favourable to demolish and rebuild. The structure of the office block, however, could last twice as long as the current building life of fifty years. The rolling mill is the only product for which the structure is fully exploited (no residual lifespan), finally failing due to fatigue after one hundred years.

The y-intercepts of the step-graphs show that all four products have a long-lasting structure that accounts for the largest initial steel mass share. Structural components will often have the longest potential lifespan because they are subject to minimal wear, fatigue and corrosion. Comparing the y-intercepts to the cumulative masses at product end-of-life reveals that components that have a relatively low steel mass, but which are regularly replaced, can have a large impact on the steel demand rate. These are typically mechanical sub-assemblies, failing due to wear. The clearest example is the work rolls in a rolling mill which, over the mill's hundred-year lifespan, account for two new mills' worth of steel.

4. How can we reduce demand for steel by better exploiting the steel components in products?

The mass of steel required for a product to operate depends on the steel mass in initial production and the steel mass in component replacements. Reducing the demand for steel, therefore, depends on reducing the average steel demand rate (the steel used in a product spread over its lifetime), which is a function of both these quantities. For products where there are no component replacements (such as the washing machine), comparing Figs. 2 and 3 reveals that the steel demand rate is the mass of the product divided by the lifespan of its shortest-lived component. For products with component replacements (such as the rolling mill), it is the cumulative product mass divided by the product's lifespan. In this case, the cumulative product mass depends on the mass of the

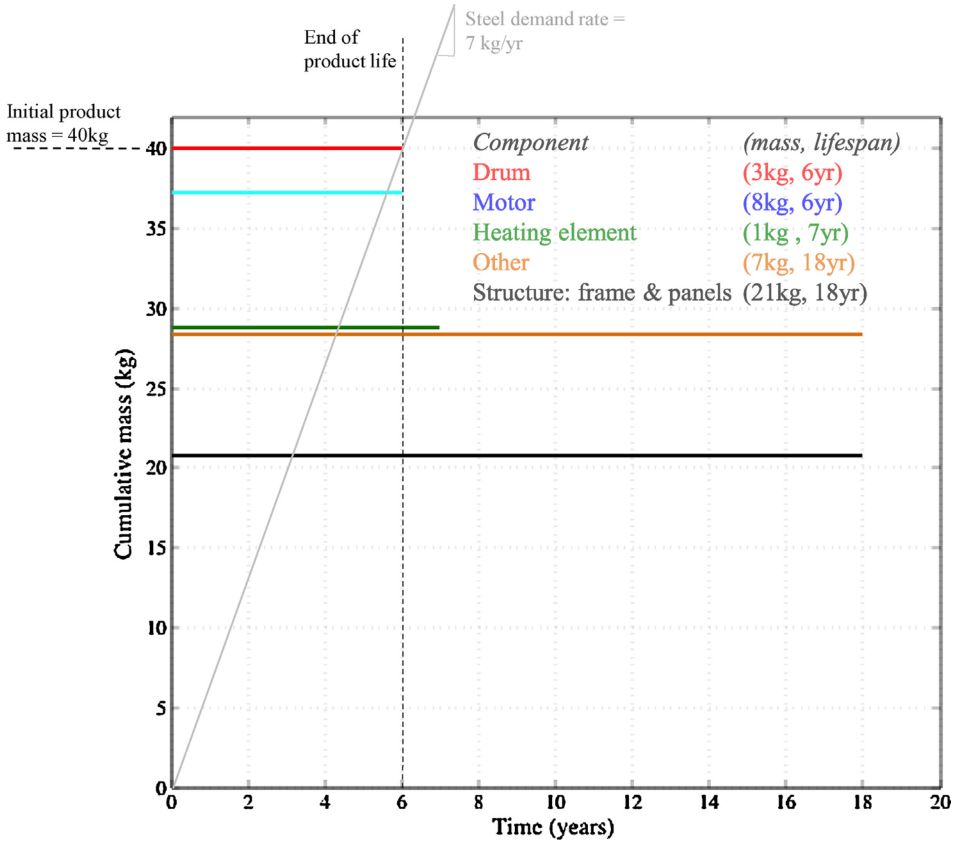


Fig. 2. Cumulative mass of washing machine components over the product's lifespan.

components and the rate at which they are replaced. The product lifespan will correspond to the failure of one or more components.

In both scenarios, increasing the actual lifespan of high cumulative mass components will reduce the steel demand rate significantly. The structure, if under-exploited, typically accounts for a high proportion of the cumulative mass. Therefore, there are two complementary objectives for reducing steel demand by increasing the average lifespan of steel in products:

1. Reduce the residual lifespan of under-exploited structural components:
   (a) By facilitating replacement of short-lived components.
   (b) By extending the lifespan of short-lived components.
2. Increase the lifespan of components with high cumulative mass.

Fig. 4 shows how the calculation for the cumulative mass step-graphs of the washing machine and rolling mill (Figs. 2 and 3c) changes when these strategies are applied to the same mass and lifespan data set. Light weighting of components, without any increases to their lifespan, would also reduce the steel demand rate. This has been addressed by Carruth et al. (2011) and is not studied further here.

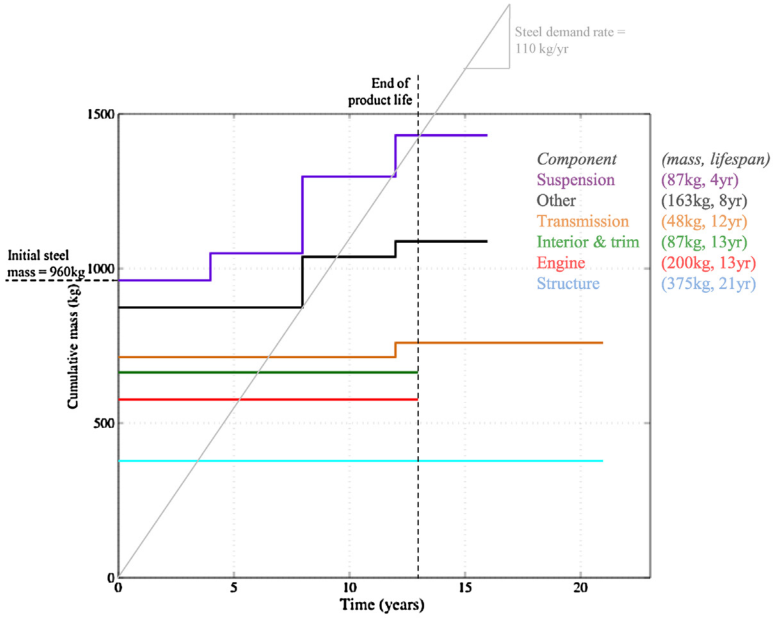
Fig. 4a shows the modelled cumulative mass over time of a washing machine assuming that the drum, motor and heating element can all be easily replaced, fully exploiting the potential lifespan of the steel rich structure. This reduces the washing machine's steel demand rate from 7 to 3.4 kg/yr. Therefore, the structure's residual lifespan, and the product's steel demand rate, can be reduced by either extending the lifespan of shorter-lived components, or allowing them to be easily replaced. Increasing the potential lifespan of a component with residual life (such as the washing machine structure in Figs. 2 and 4a) will have no affect on the steel demand rate because it will neither decrease the cumulative mass nor increase the product's actual lifespan.

Increasing the lifespan of short-lived components decreases their cumulative mass and can greatly reduce the product's steel demand rate. Fig. 4b represents a rolling mill where the lifespan of the work rolls has been increased from five to ten years. This decreases the rolling mill's steel demand rate from 250 to 210 te/yr.

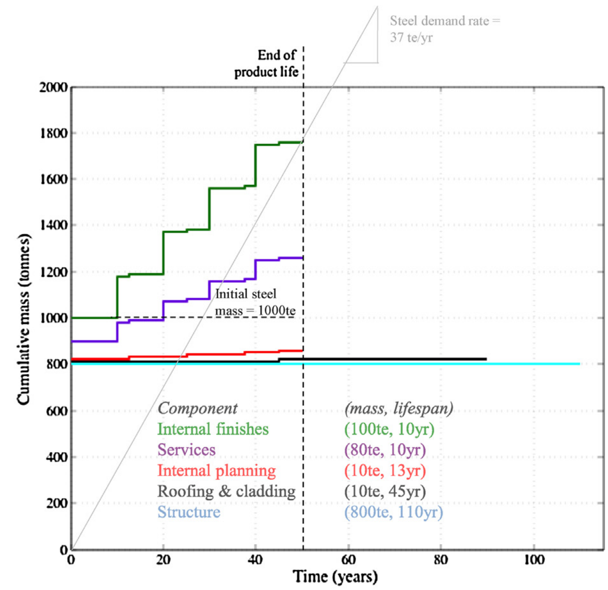
An office block structure (Fig. 2b) has a high residual lifespan and dominates the cumulative mass. Applying the objectives above, either the lifespan of the internal planning should be increased or it should be made easily replaceable, reducing the structure's residual lifespan. Similarly, either increasing the lifespan of a car's engine or making it easier to replace would reduce the residual lifespan of a car's structure (Fig. 2a). Increasing the lifespan of a car's suspension would also be worthwhile as the suspension can account for a large proportion of a car's cumulative mass.

5. What pragmatic strategies are associated with these objectives?

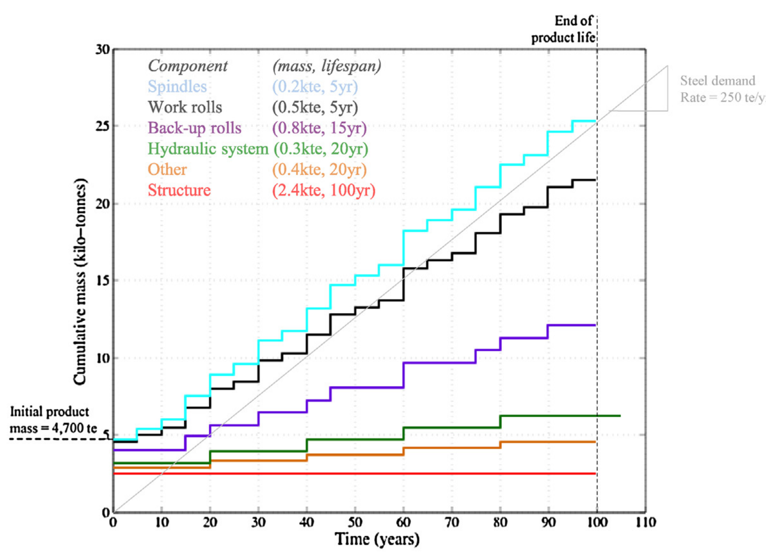
To achieve the objectives set out in Section 4, designers and maintenance engineers require practical strategies. They also need to know which product failure mode each strategy is applicable to. A set of twelve 'case study interviews' with industry and academic experts (who are experienced in extending the lifespan of products and components) was conducted in order to identify strategies to address product and component failure. Each interview covered the causes of failure, the technical strategies that had or could be applied to extend product or component life, and the motivations for these strategies. The resulting evidence on motivations is used in Section 6. Table 4 provides a summary of the interviews conducted.



(a) car



(b) office block



(c) rolling mill

Fig. 3. Cumulative mass of components over the products' lifespans. (a) Car; (b) office block; (c) rolling mill.

Table 4
Interviews undertaken to investigate lifespan extension strategies.

Case study	Sector	Interviewee/Source
Refurbishing modular buildings	Construction	Technical Manager, Foreman's Relocatable Building System
Steel rolling mills: replaceable work roll sleeves	Industrial equipment	Technology Manager, Siemens VAI
Adaptable foundations	Construction	Director, Arup
Adaptable, robotic packaging equipment	Industrial equipment	A fast moving consumer goods manufacturer
Durable infrastructure	Construction	Professor, University of Cambridge
Hard-wearing rails, replacing rails & resurfacing tram rails	Construction	Programme Manager, Network Rail
Carbon-fibre aircraft body	Transport	Technical Fellow, Boeing
Restoring supermarket equipment	Metal goods	Development Manager, Tesco
Office block refurbishment	Construction	Associate, Expedition Engineering
Steel mill upgrade	Industrial equipment	Senior Academic, Manchester Business School
Upgradable washing machine	Metal goods	Director, ISE appliances
Component reuse of oil rigs	Construction/Industrial equipment	Project Director, Able UK

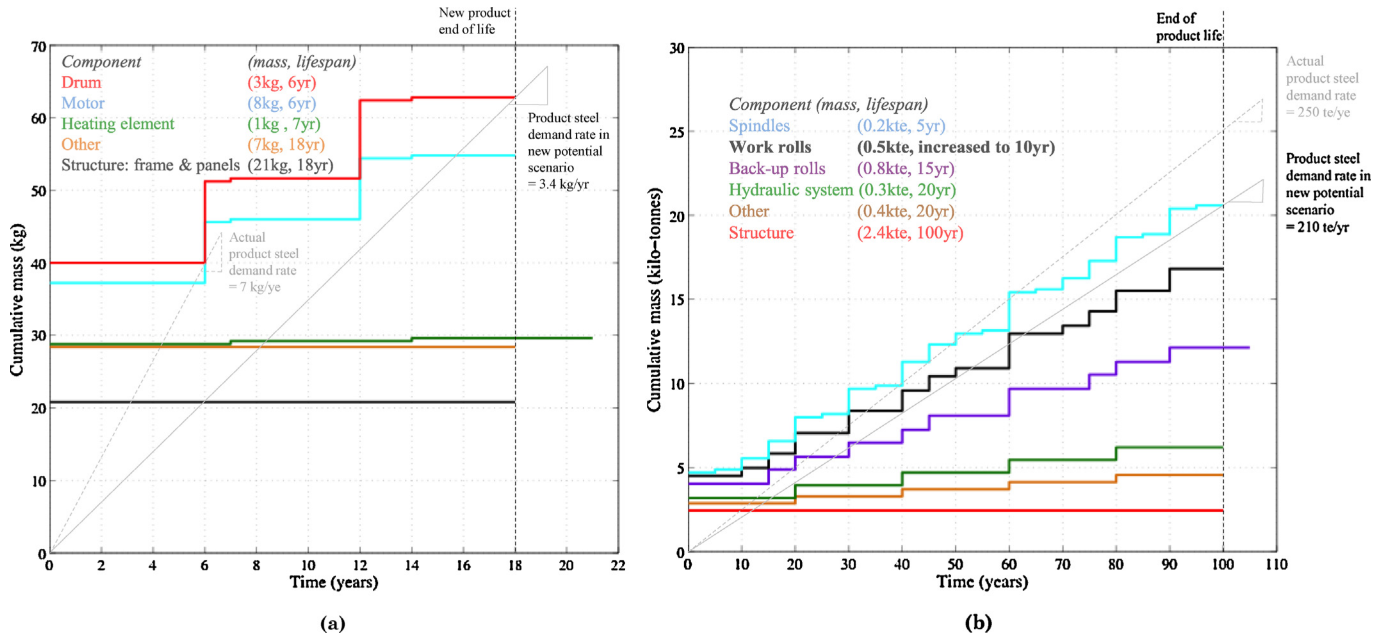


Fig. 4. New potential scenarios. (a) Reducing the residual lifespan of the washing machine structure by replacing short-lived components; (b) reducing the steel demand of rolling mill work rolls by increasing their lifespan.

Details of each case study interview can be found in the S.I. accompanying this paper. Transferable lessons were identified from each case study and the resulting strategies were tailored to the four types of failure: *degraded*, *inferior*, *unsuitable* and *worthless*.

From the interviews it became apparent that knowledge of the anticipated failure mode determines the type of life extension strategy that can occur. When the cause of failure can be foreseen, measures can be taken to *design-out* the features that cause failure. For example, high strength, hardwearing rail track can be used to mitigate against rail-head wear that causes failure. When the exact failure is less certain, or when design-out solutions do not exist, features can be incorporated into the design that prevent product failure by providing sufficient flexibility to adapt or replace components. These strategies are referred to as *design-in* strategies (e.g. designing foundations to allow for different building configurations). The interviews revealed that maintenance strategies are the same as design strategies, but applied during the product's life. Fig. 5 shows the strategies and their relevance to each of the four failure modes.

6. What would motivate us to adopt these strategies?

Section 4 identified two objectives to reduce demand for steel: (1) components that fail early should be easily replaceable or have their life extended (to exploit the long lived structure) and (2) the life of steel rich components should be extended. Consumers are likely to help meet these objectives if component costs and component steel content are positively correlated: this would mean that light, short-lived components could be replaced at relatively low cost and that it would take longer to write-off steel rich components. Producers, however, are more likely to contribute to meeting these objectives where high margins can be made on short-lived replaceable components. This business strategy has been adopted, for example, for printers (where margins are made on cartridges), coffee machines (where margins are made through the sale of coffee capsules, for example nespresso) and cameras (where margins are made on film, for example the sale of Polaroid film prior to the dominance of digital photography).

This section presents findings on the configuration of product component costs and explores the extent to which the above statements apply to the four case study products. The cost data for the products are presented in Table S1 of the S.I. The data for the car and the steel rolling mill were supplied by a car manufacturer and an equipment manufacturer under the condition of anonymity. Office block and washing machine component cost data were taken from Goodchild (1993) and Siemens (2012), respectively. The cost data for the car reflects the component costs faced by a luxury car manufacturer: it includes the cost of raw materials, the cost of intermediary inputs (including profits charged by suppliers on these), and value added (e.g. component labour costs); it excludes any margins that could be charged by the car manufacturer on selling these components individually to customers. The cost data for the steel rolling mill, the washing machine and the office block reflects the price that is paid by the purchaser: in addition to all producer component costs, profit margins charged by the supplier are included. In all cases costs are expressed as an index, with initial total component costs equal to one.

Fig. 6 presents cumulative cost step-graphs for the four representative products, analogous to the cumulative mass step-graphs reported in Figs. 2 and 3. As replacement costs for components are incurred at different points in time, future costs must be discounted to reveal their current value. The appropriate discount rate depends on factors such as the cost of capital to the user, risk preferences and opportunity costs. In Fig. 6 a rate of 10% was used. This lies between the 3.5% recommended by the UK Treasury (HM Treasury, 2003) for evaluating government projects and the 15% used by a fast moving goods manufacturer to justify purchasing decisions (S.I., case study 4). The wide variation reflects the challenge of accurately identifying an appropriate discount rate across all product categories. Fig. 6 presents the effect of using one possible discount rate within the given range; the estimated costs and timings should therefore be viewed as indicative rather than definitive.

Fig. 6 includes the same steel rich components for each product as in Figs. 2 and 3. For all products except the car, the most expensive component does not contain the most steel (either initially or over the lifetime of the product). The components with

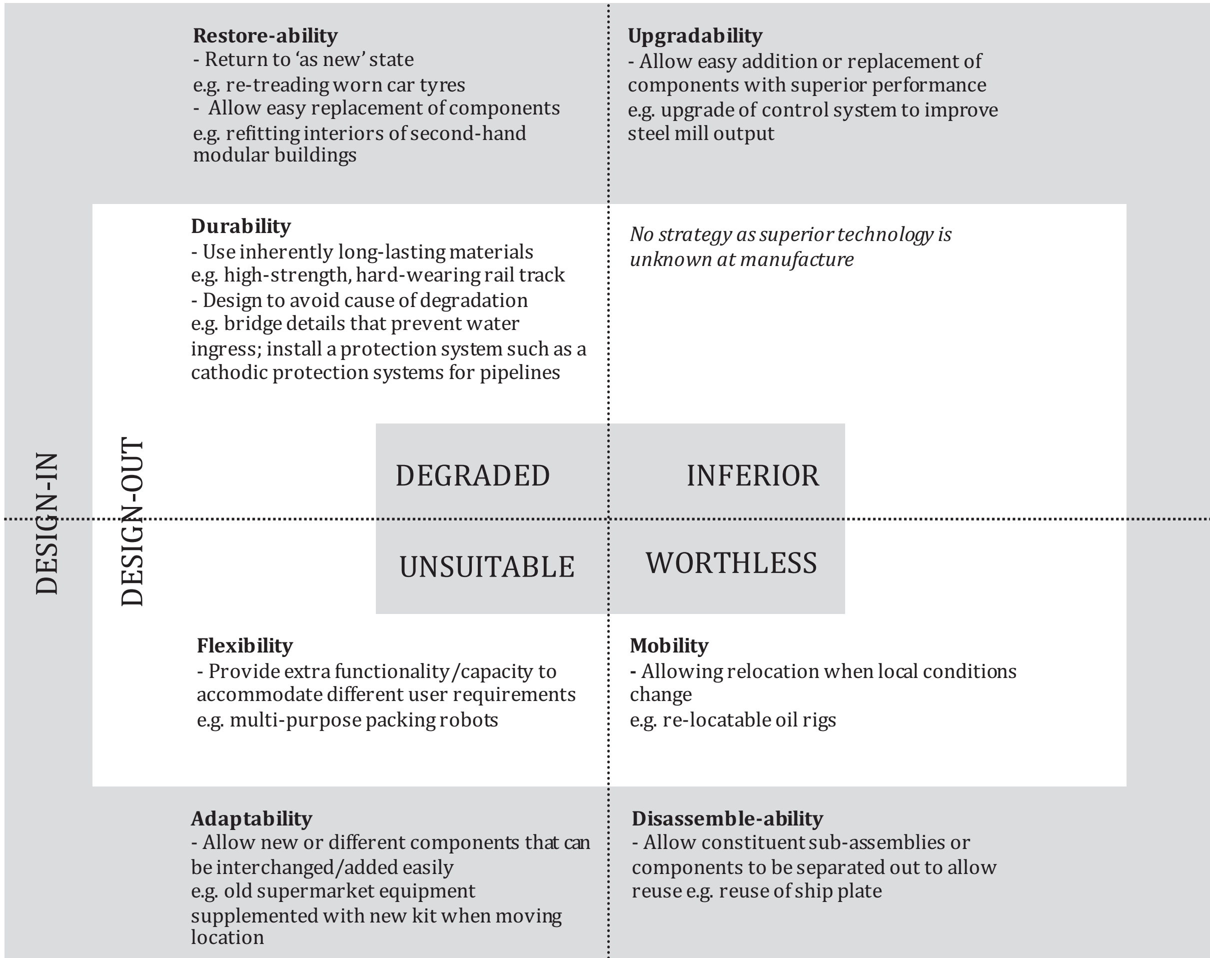


Fig. 5. Targeted strategies to address product and component failure.

the highest cumulative cost shares are the services in the office block and the electronic and control systems (part of the 'other' category) in the rolling mill and the washing machine. The car is the only product for which the most expensive component also has the highest steel content; this is likely due to the high quality of the material used by this luxury car manufacturer. For the car and the washing machine the most expensive components are not replaced; however, for the rolling mill and the office block these relatively high cost services and control systems are replaced when they become inferior. This suggests that the relatively high cost of manufacturing and installing components does not deter replacement if the replacement parts offer enhanced functionality.

Just as high component cost shares do not necessarily deter replacement, low component cost shares do not necessarily mean that replacement will occur. For example, the bearings in a washing machine drum are relatively cheap but are not replaced because they are inaccessible due to integrated design. Products that fall into this category are prime candidates for redesign by applying the strategies mentioned in the previous section.

Comparing the y-intercepts to the cumulative costs at product end-of-life reveals that the proportions do not vary between initial and final stages as much as the corresponding cumulative mass graphs. This is best illustrated by considering the work rolls (Figs. 3d and 6d). The work rolls dominate the cumulative steel mass but are only 2% of the cumulative cost. Lower discount rates would result in a greater positive correlation between cumulative component costs and steel content.

Based on the limited data provided here it is not possible to draw broad conclusions, but the findings suggest that the rolling mill template – in which the long-lived structure accounts for a relatively high share of costs and short-lived components can be easily replaced (offering profit to the producer and enhanced utility to owners) – encourages product life extension.

7. Discussion

In this section recommendations are made for extending the lifespan of the steel in the four representative products by applying the strategies presented in Fig. 5 and drawing on specific examples discussed in the case study interviews (detailed in the S.I.). More generally, the impact of applying long-life strategies on the designed level of modularity is then discussed.

A washing machine's drum bearings, a car's engine, and a rolling mill's work rolls all fail because they become *degraded*. Both *restorable design-in* and *durable design-out* strategies could be applied to prevent failure. For example, the lifespan of the washing machine (see case study 11) could be increased by designing for the motor and bearings to be replaced (easy access to motors/compressors in white goods would also allow them to be upgraded if they were superseded) or by installing more durable bearings; car engine cylinders could be made from a more

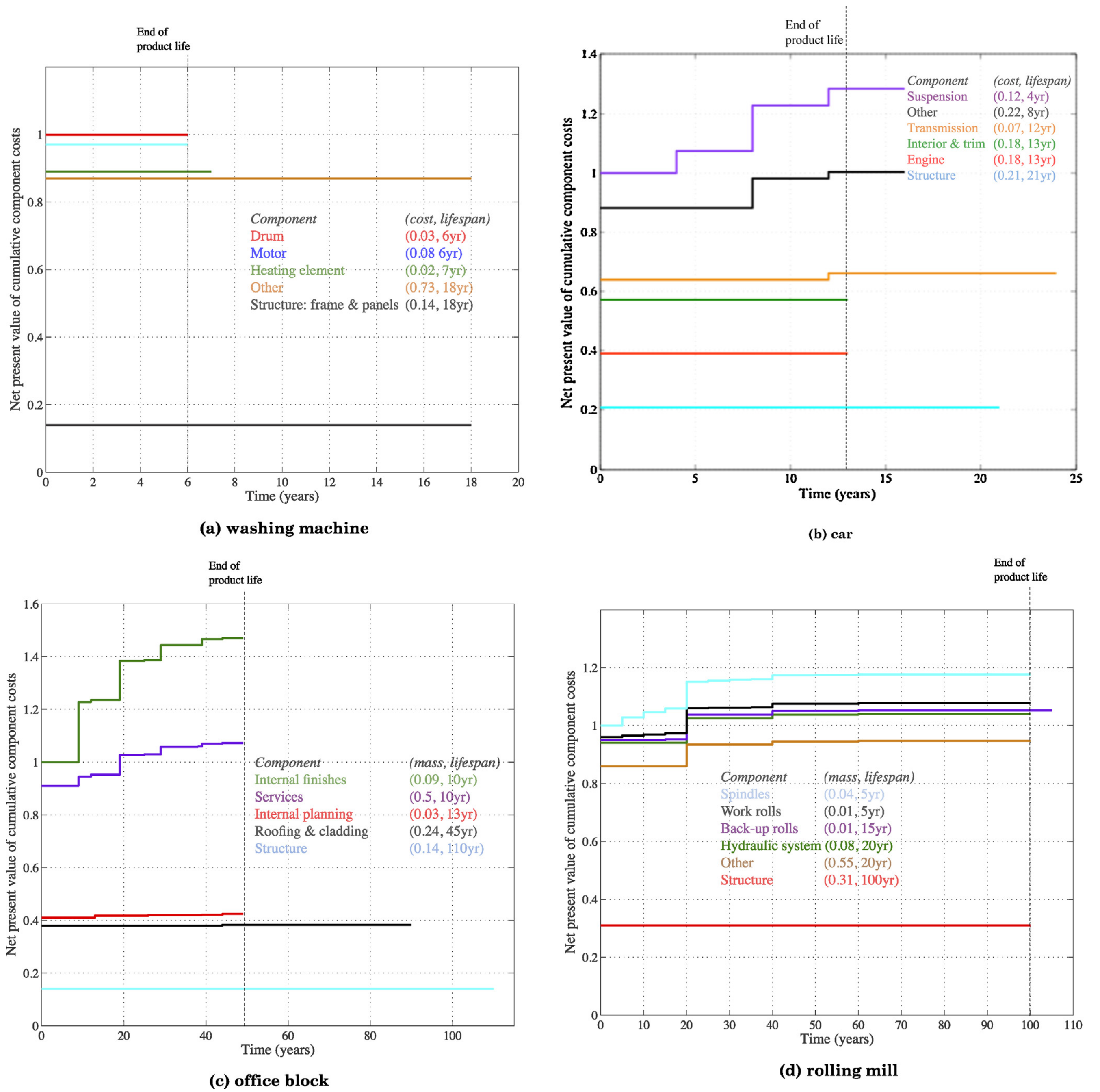


Fig. 6. Net present value of cumulative component costs over the products' lifespans. All costs indexed to initial product cost = 1. (a) Washing machine; (b) car; (c) office block; (d) rolling mill.

durable alloy, or replaceable inserts could mitigate wear. In the case of rolling mill work rolls (see case study 2), the outer layer is already made of a hard chrome steel, meaning that increasing their durability may be difficult. However, the worn surface could become restorable by using a replaceable, short-lived work roll 'sleeve' around the long-lived structural core (as suggested by Hadjduk et al. (2010)). This latter principle could be applied more generally to address other types of failure e.g. replaceable aesthetic skins could be used to tackle failure of products or components that become *unsuitable* because their aesthetics are dated.

The office block is demolished due to an *unsuitable* internal plan that is incompatible with the structure. Applying the strategies for an *unsuitable* failure from Fig. 5, the structure could be made more *adaptable*, with standard interface architecture so that modules could be replaced or extended from the existing structure to cater for new requirements (see case study 1). *Flexible* buildings also include extra space, flexible floor to ceiling heights, and extra load capacity in areas where this provision is likely to be required (see case study 9).

Some of the above strategies require the use of more durable alloys that have increased corrosion, fatigue or wear resistance. The production of some highly alloyed, durable steels (such as stainless steels) emits twice the volume of carbon dioxide released in the production of low alloy steels (Ashby, 2009). Subsequently, a product's cumulative steel mass alone is not a good indicator

Table 5
Modular design responses to product failure.

Degraded Isolate short-lived components (typically those that are subjected to wear or corrosion)	**Inferior** Isolate components that are most likely to suffer due to technological change (typically electronics)
Unsuitable Isolate components that target the product to specific consumer groups (for example the internal space plan of buildings or the aesthetics)	**Worthless** Isolate components with the highest residual value (typically standardised components (e.g. structural components) with multiple alternative uses but also more complex bespoke units for which a buyer can be found)

of cumulative emissions when both low and high alloy steels are used in a product. In this scenario, step-graphs of the product's cumulative embodied emissions (rather than steel mass) over time should be constructed to help analyse the impact of any design-in or design-out strategy. This methodology can also be used to account for non-ferrous materials used in a product. Degraded failure of steel components should be considered on a case-by-case basis to determine the trade-off between selection of a more durable alloy and other design-in and design-out strategies.

The design strategies summarised in Fig. 5 show that all four types of failure could be tackled through some form of modularisation (isolating the components that have failed and so extending the life of the remaining components). Examples from the interviews include restoring worn tram rails, upgrading steel rolling mill control systems, adapting building design whilst retaining the foundations and, (in the case of unequivocal product failure) by reusing components. Considering the different causes of failure, Table 5 summarises which components should be isolated in products that fail for different reasons.

The economic viability of these strategies will have to be assessed on a case-by-case basis and take into account the multiple influences on these decisions, not only the component cost structure. Nevertheless, this paper has presented some preliminary evidence to suggest that product upgrade strategies are most likely to be viable when the source of product failure can be isolated to a subset of replaceable components that offer high value to users (as they enhance the functionality of the product) and can generate high margins for producers.

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Appendix A. Supporting information

The supporting information for this paper contains summaries of the case study interviews presented in Section 5, and the component level data used to create figures 2, 3, 4 and 6. It can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2013.11.014.

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